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New cooling approach and tool life improvement in cryogenic machining of titanium alloy Ti-6Al-4V

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Abstract

Titanium alloy Ti-6Al-4V, a difficult-to-machine material because of its extremely short tool life, has been a major subject for cryogenic machining research. However, the approaches reported in past publications are inherently flawed. This study reviews how the temperature affects Ti-6Al-4V properties, and compares different cryogenic cooling strategies. Based on these findings, a new economical cryogenic cooling approach is proposed. Using a minimum amount of liquid nitrogen (LN2), this innovation features a specially designed micro-nozzle. Formed between the chip breaker and the tool rake face, the nozzle lifts the chip and injects focused LN2 into the chip–tool interface at the point of highest temperature. As the nitrogen evaporates, a nitrogen cushion formed by evaporating nitrogen lowers the coefficient of friction between the chip and the tool. An auxiliary mini-nozzle that sprays LN2 onto the flank at the cutting edge further reduces the cutting temperature. The study finds that the combination of these two micro-nozzles provides the most effective cooling while using the lowest LN2 flow rate. Improving the position of the nozzle/chip breaker further enhances the performance. Our cryogenic machining tests show that tool life increases up to five times the state-of the-art emulsion cooling, outperforming other machining approaches.

Keywords: Titanium machining; Cryogenic machining; Tool wear; Tool life; Nozzle design

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1. Introduction

Titanium is a relatively lightweight metal that provides excellent corrosion resistance, a high strength-to-weight ratio, and good high temperature properties. Pure titanium is allotropic, with an HCP crystal structure (α phase) at low temperatures and a BCC structure (β phase) above

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882°C. Alloying elements have the effects of strengthening solid solutions and changing the allotropic transformation temperature. Ti-6Al-4V is the representative system of $\alpha+\beta$ alloys, and is the most commonly used alloy in the aerospace industry. It accounts for about 50% of total titanium production.

Titanium and its alloys are classified as difficult-to-machine materials. The main problems in machining them are the high cutting temperatures and the rapid tool wear. Most tool materials wear rapidly even at moderate cutting speeds. To minimize tool wear, current machining practice limits the cutting speed to less than 1 m/s. The machining characteristics for titanium and its alloys are summarized below [1–4].

1. Titanium and its alloys are poor thermal conductors. As a result, the heat generated when machining titanium cannot dissipate quickly; rather, most of the heat is concentrated on the cutting edge and tool face.
2. Titanium has a strong alloying tendency or chemical reactivity with the cutting tool material at tool operation temperatures. This causes galling, welding, and smearing, along with rapid wear or cutting tool failure.
3. During machining, titanium alloys exhibit thermal plastic instability which leads to unique characteristics of chip formation. The shear strains in the chip are not uniform; rather, they are localized in a narrow band that forms serrated chips.
4. The contact length between the chip and the tool is extremely short (less than one-third the contact length of steel with the same feedrate and depth of cut). This implies that the high cutting temperature and the high stress are simultaneously concentrated near the cutting edge (within 0.5 mm).
5. Serrated chips create fluctuations in the cutting force; this situation is further promoted when alpha–beta alloys are machined. The vibrational force, together with the high temperature, exerts a micro-fatigue loading on the cutting tool, which is believed to be partially responsible for severe flank wear.

Titanium and its alloys represent the most challenging materials in machining. With advances in cutting tool materials, many difficult-to-machine materials can now be machined at higher metal removal rates. None of these tool materials, however, seems to be effective in machining titanium because of their chemical affinities with titanium. New development in tool coating also does not help titanium machining. Al_2O_3 coating has a lower thermal conductivity than the tungsten carbide insert, which prevents heat dissipation from extremely concentrated high stress and high temperature at the cutting point. Titanium carbide and titanium nitride coatings are not suitable for machining titanium alloys because of their chemical affinities. Thus, cryogenic machining, which is able to both lower the cutting temperature and enhance chemical stability of the workpiece and the tool, is expected to greatly increase productivity level in the machining of titanium and its alloys.

Most cryogenic machining studies on titanium and its alloys [5–14] have documented improved machinability when freezing the workpiece or cooling the tool using a cryogenic coolant. However, as discussed in the next section, inherent weaknesses exist in these approaches. Recent improvements in state-of-the-art conventional machining further negate the advantages reported in these studies.

Prompted by the environmental concern about conventional cutting fluid, cryogenic machining has received increased attention with the aim of finding an economical and ecological alternative for metal cutting industry. Under the cooperation of 12 US companies representing the machine, tool, cryogen, automobile, and aerospace industries, this study was part of the research program to develop an economical cryogenic machining approach for high speed cutting of difficult-to-machine materials. The goal was to find the most effective cryogenic cooling approach that will yield the longest tool life while using minimum amounts of liquid nitrogen (LN2). After initial tryout of machining Ti-6Al-4V, the cryogenic machining approach by flooding LN2 yielded very good results compared to dry cutting; unfortunately the tool life was just close to the state-of-the-art conventional emulsion cooling as described later in this paper. This result indicated that to make cryogenic machining a viable process would require improvements through comprehensive theoretical study and practical system development. Since then, the following studies have been conducted: (1) cryogenic temperature effects on the material properties of both workpiece [15] and tool material [16]; (2) cutting temperatures and different cooling approaches [17]; (3) friction and cutting forces [18]; (4) design improvements for a new cryogenic nozzle and delivery line. Applying the results of these studies, an innovative approach was adopted and it emerged as the most effective cryogenic machining system. This paper discloses the design of our innovative cryogenic machining system, and reports the effectiveness of this approach for improving tool life.

2. New approach for cryogenic machining

2.1. Temperature effect on material properties and cooling considerations

Annealed Ti-6Al-4V has a microstructure consists of a coarse, plate-like alpha phase and a grain boundary beta phase. Its strength and the elongation with respect to temperature change [19–21] are presented in Fig. 1. Our own findings on titanium and its variation in hardness with temperature change are shown in Fig. 2. As shown, the strength of Ti-6Al-4V increases rapidly as the temperature is decreased. For instance, when titanium changes from room temperature to liquid nitrogen temperature, tensile strength changes from 1000 to 1700 MPa. This means that the cutting force will increase, consuming more power and generating more heat. With regard to impact strength, tensile elongation and reduction in area, the research literature is not consistent. However, most data showed that even at liquid nitrogen temperature Ti-6Al-4V sustains its toughness and ductility, without the apparent ductility to brittleness transition common for carbon steels. Cooling the material does not improve the chip as in the successful case of cutting low carbon steel reported in [22]. On the other hand, the hardness of Ti-6Al-4V increases quickly as the temperature decreases. Thus, the decreased temperature of the workpiece tends to increase the abrasion of the chip to the cutting tool. Clearly, cryogenically cooling the workpiece is not desirable.

Cutting temperatures for Ti-6Al-4V can easily reach 1000°C, which will soften the cutting tool material and accelerate tool failure. When LN2 is used to cool the tool cutting edge surfaces, the increased hardness of the tool can improve the tool wear and expand the tool life. Our tool material study [16] showed that the strength and harness of the carbide tool material increased

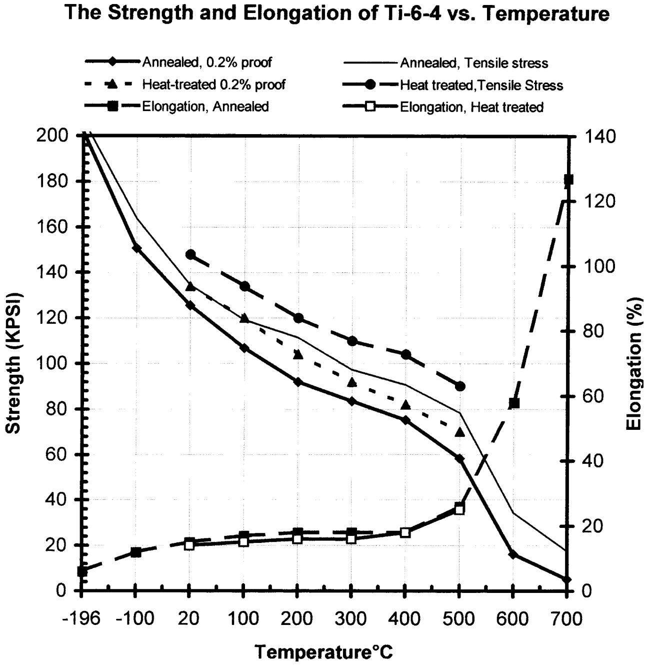

Fig. 1. The strength and elongation of Ti-6Al-4V versus temperature.

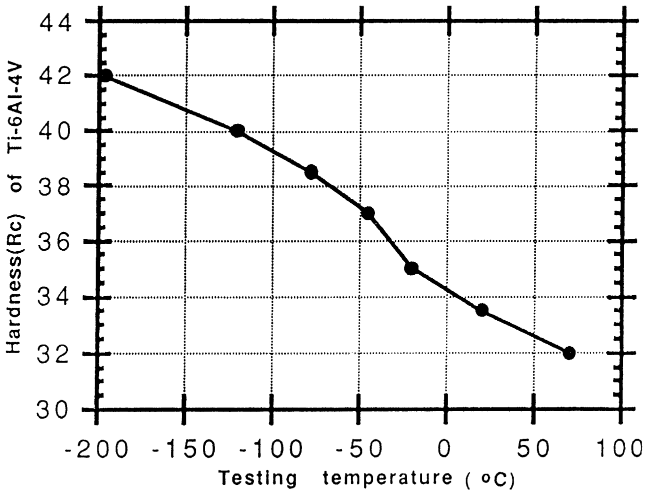

Fig. 2. The hardness of Ti-6Al-4V versus temperature.

under cryogenic temperatures, but the impact strength was not weakened. As result of material studies, it is recommended that the cutting tools, but not the workpiece materials, be cooled.

In the past, common cryogenic machining cooling approaches have included: (1) pre-cooling the workpiece [11], (2) indirect cooling [12,23], (3) general flooding [24], and (4) an enclosed bath [9,10]. Each of the approaches as reported in the cited research has flaws. Pre-cooling the workpiece and enclosing the workpiece in a cryogenic bath are not practical in the production line and negatively increase the cutting force and the abrasion to the tool. Indirect cooling by thermal conduction through the tool body is highly dependent on the thermal conductivity of the tool material and the distance from the LN2 source to the highest temperature point at the cutting edge. In general, indirect cooling is not effective. General flooding, like conventional emulsion cooling, is favored by many; however, this approach wastes a large amount of liquid nitrogen, often cooling unwanted areas causing a negative effect such as pre-cooling the workpiece. Currently, no cryogenic cooling approach exists that is economical and practical enough to replace conventional machining.

2.2. New economical cryogenic cooling approach

This paper introduces an innovative cryogenic cooling approach composed of the following concepts:

1. To minimize waste, cryogenic fluid is applied directly to, and only to, the tip of the cutting tool, where the material is being cut and heat is being generated.
2. The flowrate of the cryogenic fluid is proportional to the heat generated in the cutting process, preventing the workpiece from becoming distorted due to extremes of heating or cooling.
3. The micro-nozzle is located between the tool face and chip breaker as a commercial new cutting tool assembly, a design that is economical and convenient for users.

Fig. 3 exemplifies the cryogenic machining cooling concepts using a flat cutting insert with an obstruction chip breaker. Liquid nitrogen is released through a nozzle between the chip breaker and the rake face of the tool insert. The chip breaker helps to lift the chip to allow liquid nitrogen to reach and cool the highest temperature spot—the tool–chip interface. Unlike general flooding, the chip does not block the flow of liquid nitrogen. The liquid nitrogen absorbs the heat, evaporates quickly, and forms a fluid/gas cushion between the chip and tool face that functions as a lubricant. Consequently, the coefficient of friction is reduced, as well as the secondary deformation in the chip, as documented in our study [18]. Both the lubrication effect and cooling the hottest spot reduce the tool temperature, in turn effectively reducing both crater and flank wears. An auxiliary cryogenic nozzle may be added to cool the flank face near the cutting point for further reduction of flank wear.

2.3. Design implementation

Fig. 4 illustrates the nozzle for a flat cutting insert. The nozzle is formed by placing a modified chip breaker on the tool insert. Channeled grooves are etched on the bottom of a standard carbide chip breaker. Liquid nitrogen flows from a vacuum-jacketed delivery line through a hole on the chip breaker to these channels and is released onto the cutting edge. The channels, formed by electrical discharge machining (EDM) for this study, can be economically mass-produced by molding the carbide green compact in the powder metallurgy process. The low profiled nozzle prevents the chip blocking the LN2 flow, yet the carbide construction is strong enough to resist wear by the chip.

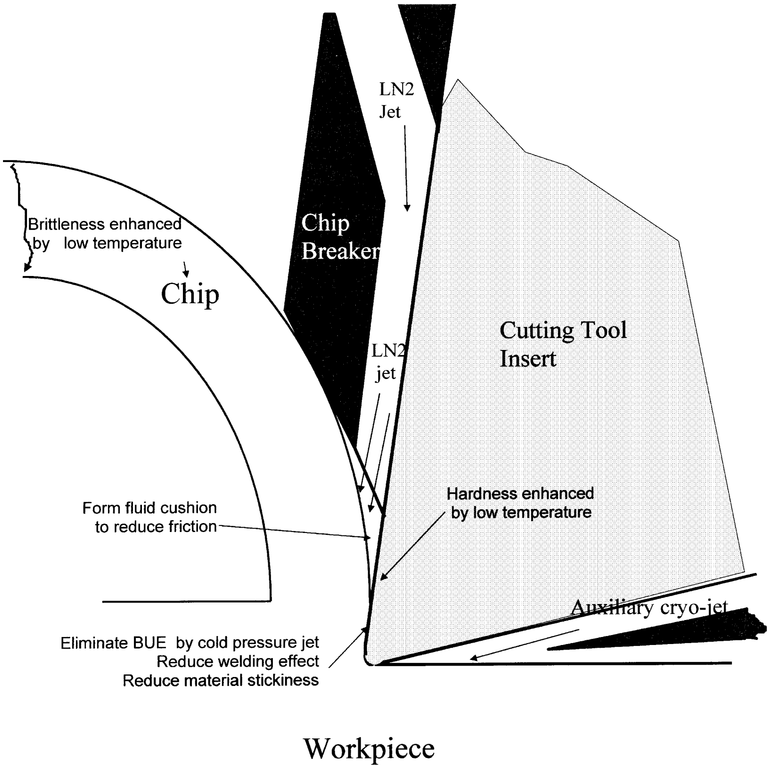

Fig. 3. A schematic of the economical cryogenic machining approach.

To accommodate severe flank wear in machining titanium, the liquid nitrogen supply can be branched to an auxiliary nozzle that sprays the cutting edge on the flank surface. In this case, the secondary nozzle is integrated with the LN2 supply block. Fig. 4(a) shows when both nozzles are used. To turn off the secondary nozzle, the block is slid back as shown in Fig. 4(b). Fig. 5 shows a photograph of the nozzle assembly with LN2 flowing. Nozzle designs were developed for differently formed tool inserts with a built-in chip breaker for machining steels [25]. Other designs have the nozzle groove built on the tool insert rather than on the chip breaker.

3. Machining tests and tool life comparison

3.1. Experiment setup

To be meaningful, evaluation of cryogenic machining must be based on realistic conditions. The machine, cutting tool, and cutting conditions must be comparable to industrial state-of-the-art standards. In this study, the machining tests were performed according to international standard ISO 3685:1993 [26]. Cincinnati-Milacron Cinturn 1408C, a 30 HP slant bed computer numerical controlled (CNC) turning center, was used for machining tests. The CNC controller is capable of maintaining a constant surface speed at different work diameters. A commercial cutting tool,

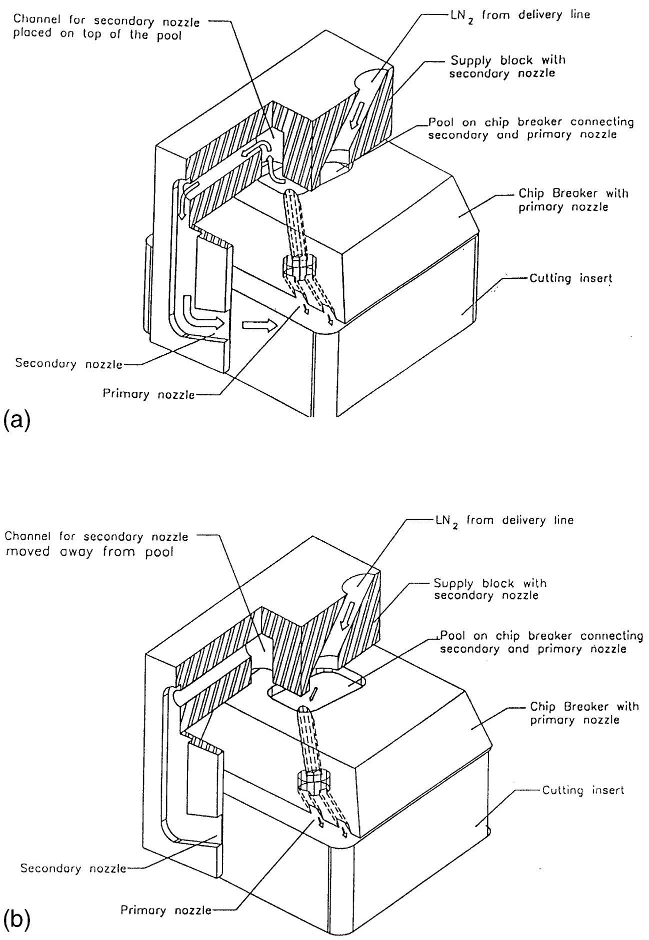

Fig. 4. The design implementation of the cryogenic nozzle. (a) When both primary nozzle and auxiliary nozzle are used to inject liquid nitrogen; (b) only the primary nozzle is used.

Kennametal insert CNMA432-K68, a typical carbide grade for cutting titanium, was mounted on the CNC's turret. This insert is a tough WC/Co unalloyed grade, equivalent to ANSI C2-C3, or ISO K05-K15, M10-M20.

When machining titanium, tool life is most affected by cutting speed, but it is also sensitive to the feed and depth of cut. A fixed depth of cut 1.27 mm (0.050 in) and feed 0.254 mm (0.010 in) was selected based on the *Machining Data Handbook* [27] and recommendations from our industrial sponsors. The cutting speed commonly used in industry is only 1 m/s (200 ft/min). Some companies have tried 1.5 m/s. With the potential for higher cutting speeds in cryogenic machining, the speeds tested in this study included 1, 1.5, 2.0, and 2.5 m/s (200, 300, 400, and 500 ft/min).

The following tool life criteria were used according to the ISO standard [26]:

1. Average flank wear: 0.3 mm, or

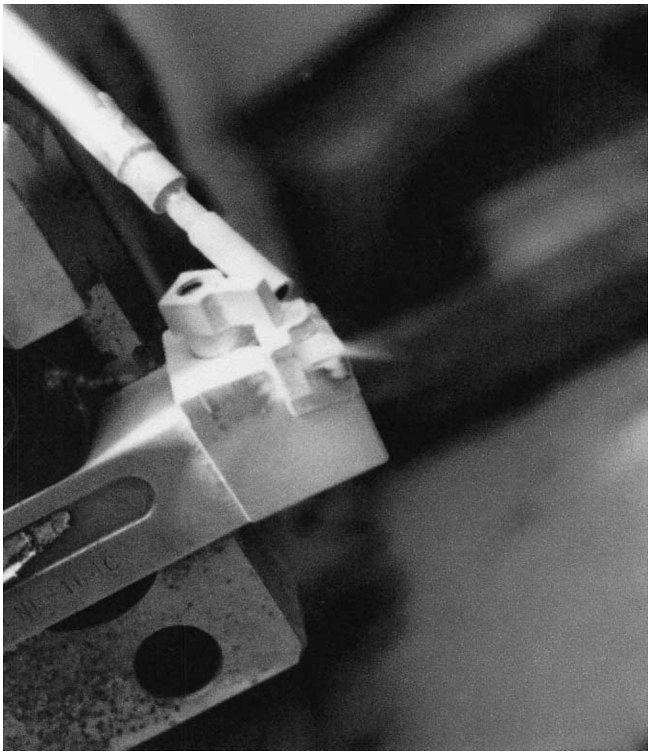

Fig. 5. A photograph showing LN2 flowing out of the nozzle.

2. Maximum flank wear: 0.6 mm, or
3. Depth of crater wear KT: 0.06 mm+0.3 x feed.

Since a comparatively low crater wear was observed consistently for all cuttings of Ti6-4, the tool life was predominantly based on average flank wear of 0.3 mm or maximum flank wear of 0.6 mm, whichever criterion it reached first. During the test, tool wear was measured by an optical microscope.

3.2. Conventional emulsion machining tests as baselines for comparison

To establish a base for comparing tool life for cryogenic machining, conventional machining tests were conducted under supervision of the machining specialists of our tool and aerospace industrial research partners. The cutting tool and workpiece were flooded with high performance commercial emulsion coolant. The emulsion cutting fluid was obtained by mixing the concentrate with water at a ratio of 1:20. The coolant flowed at a rate of 4.9 liter/min (1.35 gal/min). The tool life measured was 15 min 48 s for a cutting speed of 1.0 m/s, 4 min 56 s for 1.5 m/s, 3 min for 2 m/s and 56 s for 2.5 m/s respectively. These conventional machining tool life data are longer than reported in other cryogenic machining studies, and are believed to be the state-of-the-art according to machining specialists.

3.3. Flooding method in cryogenic machining

The flooding method of applying LN2 in machining consumed large quantities of LN2 but yielded poor tool life results. In the early stages of our cryogenic machining study, the general flooding of liquid nitrogen to the cutting tool as in conventional emulsion cooling was tested. LN2 was supplied through a vacuum-jacketed line to the cutting zone from a commercial cylinder, by its own pressure of 1.4–2.4 MPa. The volumetric flowrate was measured by a Hoffer miniature turbine flowmeter, which had been calibrated by the weight reduction of the liquid nitrogen tank on an electronic scale. Machining tests were conducted under the same cutting parameters as conventional machining.

Without using the special nozzle described in this paper, the tool life was only 5 min 26 s at 1.5 m/s when using one nozzle to flood LN2 to the general cutting area with the high flowrate of 0.019 kg/s (0.375 gal/min). This tool life is about the same as conventional emulsion cooling. Subsequently, one additional nozzle was added to cool the flank surface. The LN2 flowrate was increased to 0.056 kg/s (1.1 gal/min). When using two nozzles for general flooding, the tool life improved to 8 min 45 s.

Fig. 6 shows the results of multiple tests using flooding methods for cutting speeds of 1.0, 1.5, 2, and 2.5 m/s. The single nozzle-flooding mode has a shorter tool life than conventional machining with the emulsion coolant at the normal cutting speed of 1 m/s, and they are about the same for higher speeds. Even though using a two-nozzle flooding mode improves the tool life, it could not be economically justified due to the large volume of LN2 consumed. As described in the introduction, a more effective cryogenic cooling approach was needed. As a result of fundamental studies on aspects of material, temperature, and lubrication effects, this study redirected its focus to the new economical cryogenic cooling method, which will be discussed below.

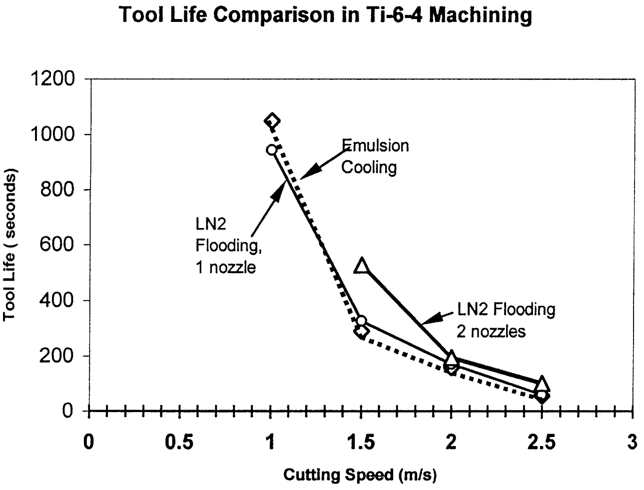

Fig. 6. Tool life comparison between flooding LN2 and emulsion cooling.

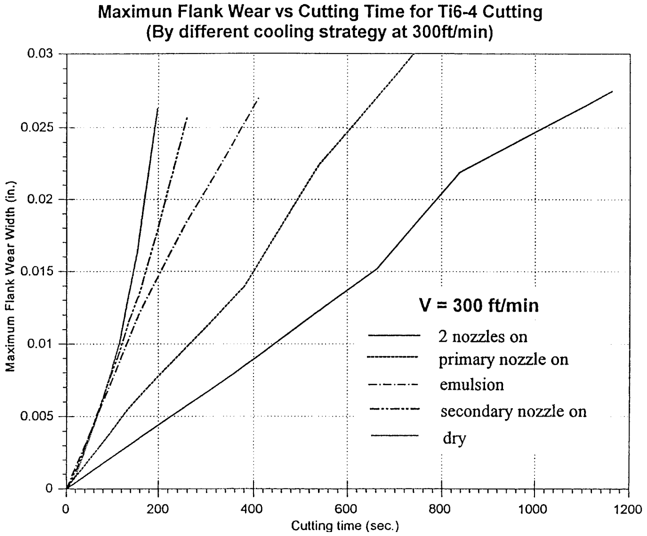

Fig. 7. Tool life comparison of different cooling approaches at 1.5 m/s (300 ft/min).

3.4. Machining test using the new economical cryogenic machining approach

The new economical cryogenic machining approach uses LN2 of low flowrate focused to the cutting point, which significantly improves the tool life. As described above, two nozzles cool the tool rake and tool flank, respectively. The effectiveness of the rake nozzle (primary nozzle) and the flank nozzle (secondary nozzle) was evaluated by the standard machining test at 1.5 m/s. The tool wear rate for different cooling methods are compared in Fig. 7. The tool life was 547 s for rake cooling by the primary nozzle (flowrate 0.49 kg/min), 238 s for flank cooling by only the secondary nozzle (0.43 kg/min), and 948 s for both rake and flank cooling by two nozzles (0.65 kg/min). For comparison, the tool life was 167 s for dry cutting and 290 s for emulsion cooling. As shown in Table 1, these test results agree with the temperature analysis using finite

Table 1
Highest temperatures at the cutting tool insert measured by the imbedded thermal couple at the tool insert and obtained by finite element (FE) analysis and their corresponding tool lives

Cooling approach	Measured (°C)	FE max (°C)	LN2 flowrate (kg/min)	Tool life (s)
Dry cutting	865	1072	N/A	167
Emulsion cooling	524	488*	N/A	290
Cooling tool back by LN2	648	787	0.91	N/A
Pre-cooling workpiece by LN2	481	408**	0.91	N/A
1 LN2 jet to flank	447	526	0.43	238
1 LN2 jet to rake	335	437	0.49	547
2 LN2 nozzles on	208	265	0.65	948

* Assume the workpiece is cooled to LN2 temperature.

** Assume a perfect distribution of emulsion to the cutting edge.

elements and thermal couple measurements detailed in the cooling approaches and cutting temperatures paper by the author [17].

Since flank wear is the main tool life criterion when machining Ti-6Al-4V, flank cooling might be a direct approach to reducing flank wear. However, directing one LN2 jet to the tool flank only was less effective than conventional emulsion cooling (i.e. higher temperature and shorter tool life). On the contrary, cooling the tool rake by the primary nozzle outperformed emulsion cooling, largely because LN2 was directed to the highest temperature on the rake. In addition, LN2 provided the lubrication between the chip and the tool rake as disclosed in another paper by the author on friction and cutting forces in cryogenic machining [18]. From this preliminary study, cooling both rake and flank provided sufficient cooling and lubrication and yielded the best tool life. Clearly, focused cooling with a small LN2 flowrate to the rake, or to both the rake and flank, are the preferred approaches for cryogenic machining.

3.5. Study of the effect of nozzle/chip breaker positioning on tool life

For the current research, the LN2 delivery nozzle was designed to reach and effectively cool those localized “hot-zones” in the cutting area with a minimized LN2 consumption. As shown in Fig. 3, the chip breaker (with an integrated nozzle) functions to lift the chip off the rake face allowing the LN2 jet to reach the tool–chip interface. To achieve this, the chip breaker must be positioned close to the tool edge. However, if positioned too near to the tool edge, the chip breaker can act as a part of the tool rake and significantly change the tool rake geometry, increasing the friction force component on the tool rake face.

Tool wear tests were performed to determine an adequate chip breaker position for cryogenic cooling when using only the primary nozzle, as described by l and λ in Fig. 8. When the angle λ was adjusted to direct the LN2 jet toward the tool–chip contact area, proper chipbreaking was observed. A fresh tool insert was used for each positioning of the chip breaker as listed in Table

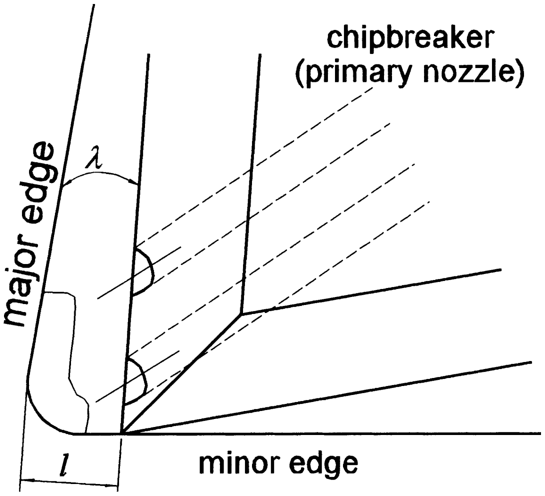

Fig. 8. Chip breaker/nozzle position

Table 2
Positions of chip breaker

Position No.	1	2	3	4	5	6
l (mm)	1.75	1.50	1.25	1.25	1.25	1.00
λ (deg)	15	15	15	20	10	10

2. The average and maximum widths of the flank wear, V_B and V_{Bmax}, as defined in the ISO standard [26], were measured under a tool microscope. The tool wear tested at a speed of 1.5 m/s is plotted in Fig. 9. Because the chip breaker at Positions No. 1 and No. 2 were too far from the cutting edge, it failed to lift up the flowing chip for the pressurized LN2 jet to reach the hot spot on the rake face. Therefore, both positions led to a high rate of flank wear. The high rate of flank wear for Position No. 6 may have been because the chip at this position (or closer) tends to block the primary nozzle and change the effective tool rake angle.

Positions No. 3, No. 4 and No. 5 each showed comparatively low rates of flank wear, with Position No. 3 producing the lowest rate. The effectiveness of the chip breaker position is again verified with tool life tests conducted twice. The averaged tool lives for Positions No. 3, No. 4, and No. 5 were 8.85, 7.80 and 7.35 min, respectively. Position No. 3 offered the best tool life. For cryogenic cooling using the primary nozzle, Position No. 3 also tends to produce a lower coefficient of friction as detailed in a previous study [18].

3.6. Full-scale machining test and tool life comparison

Table 3 lists the all the tool lives determined experimentally for different cutting speeds based on the ISO standard. The cutting tests were all performed with and without using chip breaker Position No. 3. The tool life data obtained for emulsion-cooled cutting are included here as a reference. For the cryogenic cooling, especially with “two nozzles on”, an adequate tool life can

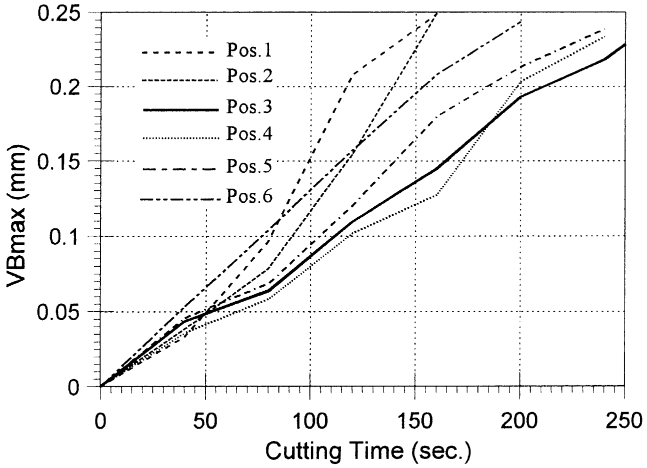

Fig. 9. Tool wear V_{Bmax} for different chip breaker positions at 1.5 m/s.

Table 3
Tool life testing result for machining Ti-6Al-4V

	Cutting speed				Coolant flowrate
	1.0 m/s (200 sfm)	1.5 m/s (300 sfm)	2.0 m/s (400 sfm)	2.5 m/s (500 sfm)	
Conventional emulsion	17′30″	4′50″	2′38″	56″	5.1 kg/min (1.35 gal/min)
LN2 cooling using only the primary nozzle at not-optimized position	19′42″	6′15″	3′05″	1′27″	0.62 kg/min (0.205 gal/min)
LN2 cooling using both nozzles, the chip breaker location is not optimized	23′15″	12′03″	6′15″	4′02″	0.84 kg/min (0.277 gal/min)
LN2 cooling with only primary nozzle with optimized chip breaker position		9′07″			0.48 kg/min (0.160 gal/min)
LN2 cooling with optimized chip breaker position (2 nozzles)	27′33″	15′48″	7′17″	4′56″	0.65 kg/min (0.215 gal/min)

be obtained even at a cutting speed of 2.5 m/min, at which even the emulsion cooling can only lead to an unacceptable tool life (less than 1 min).

For industries that refer to tool life in terms of total volume of workpiece material removed before replacing the tool, the tool life data were converted into volume removal versus speed, as plotted as in Fig. 10. Cryogenic machining dramatically increased the tool life. These increases were more significant at higher cutting speeds. For example, the tool life in cryogenic machining was up to five times longer than in conventional machining at a speed of 2.5 m/s (500 ft/min). Longer tool life in cryogenic machining allows companies to cut materials at higher speeds.

4. Discussion

The Taylor tool life equation for a fixed feed and depth of cut is generally expressed as:

$$VT^n = C$$

where T is the tool life in minutes, and V is the cutting speed in surface feet per minute. The index n depends mainly on the tool material, and C is the cutting speed for a 1-minute tool life, which is a function of the workpiece material strength and tool materials. To fit the test results into the Taylor tool life equation, the tool life was plotted against the cutting speed on a log–log scale (see Fig. 11). We obtained the following constants of the equation:

For emulsion coolant: n=0.3214, C=507.

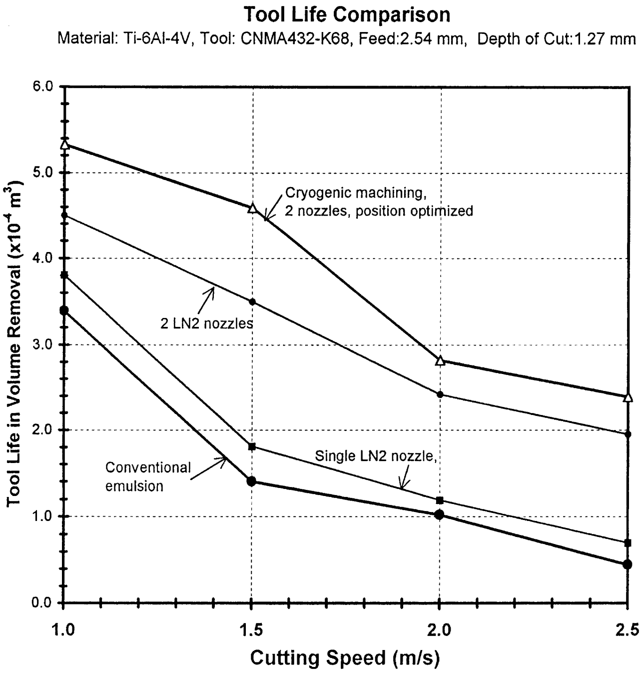

Fig. 10. Expanded tool life testing results in terms of total volume removal at different cutting speeds.

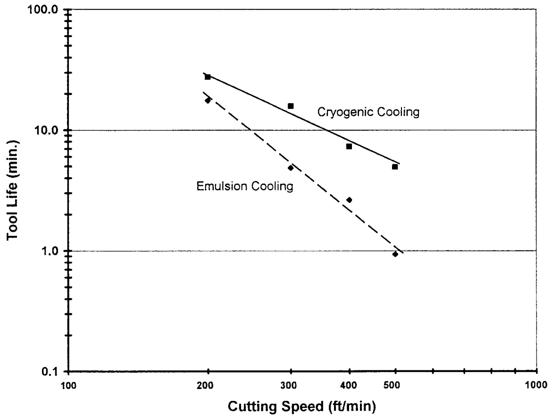

Fig. 11. Tool life comparison for cryogenic cooling and emulsion cooling curve on log–log scale.

For cryogenic machining: n=0.5164, C=1142.

From the index change, the carbide tool behaved like the ceramic tool in cryogenic machining. It also showed that Ti-6Al-4V machinability improves in cryogenic machining as the constant C increases from 506 to 1142.

The tool life obtained from this economical cryogenic machining approach is better than all known metal cutting methods, such as capping the LN2 reservoir on the tool face [13], or ultra-high-pressure water-jet-assisted machining [28]. In addition to significant machinability and tool life improvement, this new economical cryogenic machining approach also eliminated the build-up edge problem because the cold temperature reduces the possibility of chip welding to the tool and the focused LN2 jet helps to clean the edge. The work surface improved as a result of less tool wear and the build-up edge. With low LN2 consumption and excellent tool life improvement, this approach is more economical than the state-of-the-art conventional machining [29]. In total, this new cryogenic machining approach addresses the multifaceted problems that commonly occur in conventional machining; it also offers advantages not yet available in other cryogenic machining approaches.

From this study, the consumption of LN2 reduced as the tool life increased from the cryogenic flooding method to the new focused jetting approach with the optimized chip breaker position. This indicates that the cooling approach and cooling location is far more important that the LN2 amount. To deliver LN2 with a low flowrate is technically challenging even for the cryogen industry. The flowrate reduction in this study was enabled through the evolution in the delivery line design.

5. Conclusion

A new economical cryogenic machining approach has been developed. This approach uses a minimum amount of LN2 injected through a micro-nozzle formed between the chip breaker and the tool rake and assisted by the secondary nozzle for flank cooling. In this manner, LN2 is not wasted by cooling unnecessary areas and reduces the negative impact of increasing the cutting force and the abrasion of pre-cooling the workpiece material. This cryogenic machining approach yields the best tool life compared with any machining method from current known sources.

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